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Dynamics and Vibroacoustics of Machines (DVM2014)

Gas flow visualization using laser-induced fluorescence

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Abstract

Laser-induced fluorescence (LIF) is one of the methods for visualization of mixing and velocity field of supersonic flows. The method permits almost nonintrusive study of gas flow dynamics in jet engines with a high temporal and spatial resolution. The nature of supersonic flow implies large pressure, temperature and density gradients which might introduce considerable errors into the interpretation of the images, because LIF intensity strongly depends upon excited particle fluorescence decay lifetime in addition to its number density in the medium. An excited particle quenching rate usually depends on the local gas density and temperature. Therefore, for correct interpretation of the images it is necessary to know the temperature dependence of the quenching rate constants. In this work the method is developed to measure the temperature dependence of the quenching rate constant of the fluorescing particle using LIF.

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Keywords: Visualization; laser-induced fluorescence; rate constant; supersonic nozzle; iodine

1. Introduction

Imaging of fluid dynamic flowfields is a matter of practical interest to both experimentalist and theoreticians. Conventional diagnostic methods using Pitot tubes, hot-wire probes, particle image velocimetry (tracers), etc., in principle, provide a wealth of information about the flow characteristics but perturb the flow. Non-intrusive

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diagnostics, particularly those using coherent radiation to generate a secondary radiative response from the particles in the gas, are attractive because they provide a local measurements of flow characteristics with minimal perturbation of the flow. In the case of supersonic nozzle flow fields, laser induced fluorescence (LIF) techniques are suitable for a variety of reasons. The non-intrusive nature of LIF can provide detailed localized information about flow structure.

A number of particles exist which, if added to the flow and excited by a laser light, provide a sharp visualization pattern with good spatial and temporal resolution [1, 2]. One of those particles is the iodine molecule, I_2, which is conveniently observed using the $B^3\Pi(0^+)$-$X^1\Sigma^+$ transition. The advantages of this molecule are: broad and intense absorption band in the visible region, fluorescence in the visible region suitable for fast and sensitive CCD cameras, relatively large saturated vapor pressure, and a short radiative lifetime.

The compressible nature of the flow is exhibited in supersonic flow fields, where large changes in pressure, temperature, and local species densities occur within the field that must be accounted for in making quantitative interpretations of LIF generated imaging. The development of a model for the I_2 fluorescence that accounts for the thermodynamic variations while describing the spatial variation of photon production is useful from the following standpoint. It allows for quantification of the compressibility effects from an interpretive standpoint, while at the same time providing a tool for validation and verification of computational fluid dynamic models.

The planar-LIF technique with molecular I_2 was used to visualize the mixing process of the ejector nozzle unit in a chemical oxygen-iodine laser [3]. Figure 1 shows an image of the iodine luminescence excited by an argon laser at a wavelength λ = 514.5 nm. Figure 1 clearly shows the mixing process of iodine (light areas) and nitrogen (dark areas) flows.

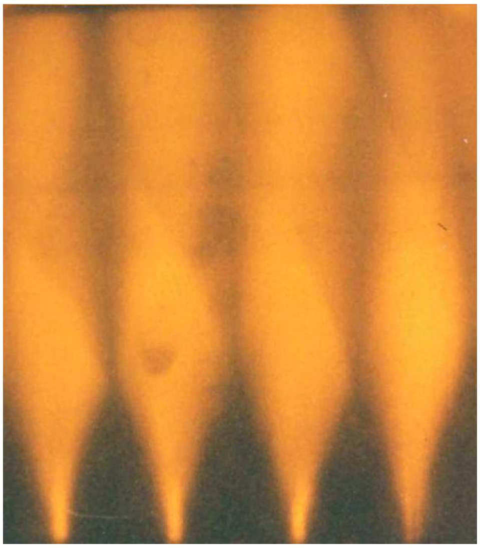

Fig. 1. LIF image in the output of the ejector nozzle unit of a chemical oxygen-iodine laser [3].

Together with the dependence on concentration, the LIF intensity also depends on the fluorescence quantum yield (Φ_f) in the medium. This is defined by

$$\Phi_f = \frac{\Gamma_{rad}}{\Gamma_{rad} + \Gamma_{nr}}$$

where Γ_{rad} is the radiative decay rate and Γ_{nr} is the rate for non-radiative decay processes. The latter includes spontaneous predissociation and collisional quenching. For quenching by a single component of the gas flow (M), the non-radiative decay rate is given by

$$\Gamma_{nr} = \Gamma_{pre} + k(T)[M]$$

where [M] is the number density for the quencher and k(T) is the temperature dependent quenching rate constant. In a supersonic expansion the local temperature is a strong function of the position within the flow. As a consequence, for precise interpretation of an LIF image it is necessary to know the dependence of the quenching rate constant (in our case for $I_2(B,v)$) on temperature.

In this article the measurements of $I_2(B)$ quenching rate constant by N_2 over the temperature range from 150 to 295 K has been performed using supersonic expansion cooling and LIF.

2. Experimental setup

Figure 2 shows the nozzle assembly used for these measurements. The cross-section of nozzle throat was 2×20 mm^2. Gas pressures were measured in subsonic P_1, transonic P_2 and supersonic P_3-P_{10} regions of the flow. A Pitot tube was used to measure the total pressure at the nozzle exit. The gas flow through the nozzle consisted of carrier gas M (where M=N_2, O_2 or He) with iodine vapor. I_2 was seeded in this stream by passing M over I_2 crystals at ambient temperature. The iodine vapour concentration was controlled by light absorption from Xe lamp at 500 nm. This nozzle was configured for Mach numbers up to 2.6, which was determined using measurements of the pressures in the Pitot tube and in the supersonic region of the nozzle.

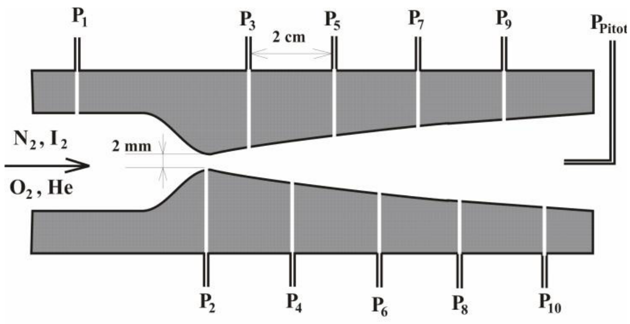

Fig. 2. Cross-section of a supersonic nozzle.

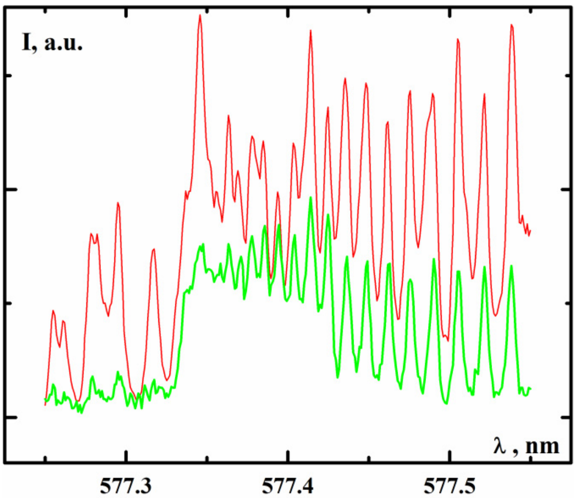

Fig. 3. Relative intensity of LIF signal (I) with dependence on wavelength of the exciting laser radiation. The upper curve is for T = 295 K, the lower curve for T = 130 K.

Transition $I_2(X\rightarrow B)$ was excited by short pulses from a tunable dye laser (operating near 577 nm) pumped by the second harmonic of a Nd/YAG laser. The line width of laser radiation was 0.06 cm^{-1} and was sufficient to resolve the rotational structure of the B-X transition. The laser beam was directed perpendicular to the gas flow 5 cm downstream from the nozzle throat. Laser-induced fluorescence was detected by looking along the flow axis. Rotational temperatures were derived from the data using a spectral simulation program [4]. Figure 3 shows the dependencies of the LIF signal intensity (I) on wavelength λ of the exciting laser for gas temperatures of T = 295 K and 130K.

3. Results

The time-dependences of LIF signal for three values of the gas temperature T in the nozzle are presented in Fig. 4. Obviously deactivation time increases with a decrease of temperature T.

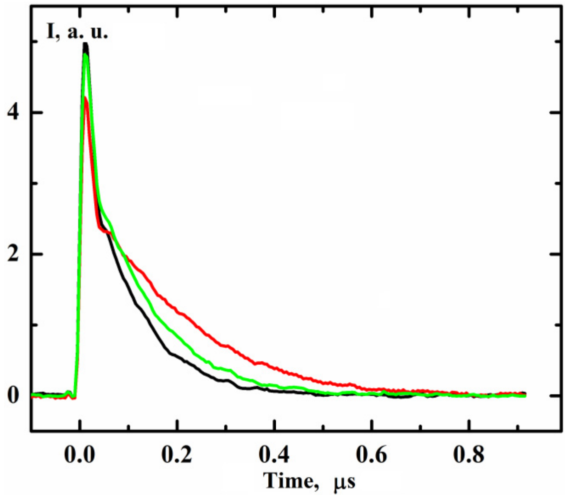

Fig. 4. Typical time evolution of relative intensities (I) of LIF signals at P_7=2.5 Torr for the three gas temperatures: 117 K - red curve, 144 K - green curve and 295 K - black curve

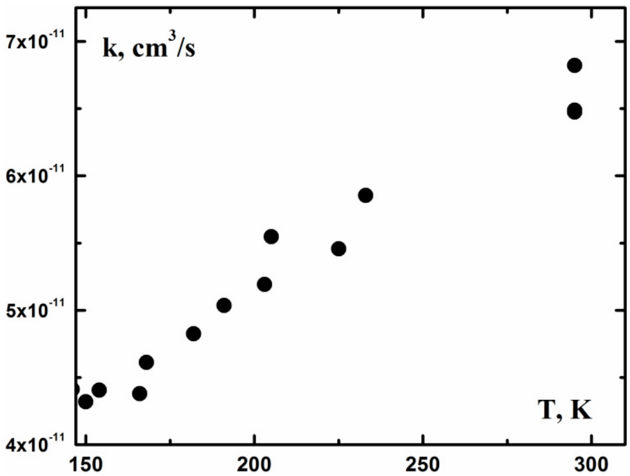

Fig. 5. Temperature dependence of the rate constant of $I_2(B)$ deactivation by N_2.

From the dependence of $I_2(B)$ fluorescence decay rates, determined from curves similar to those shown in Fig. 4, the rate constants (k) for quenching by N_2 were determined over the temperature range from 150 to 295 K. Figure 5 shows the values of the rate constants of $I_2(B)$ deactivation by N_2. It is evident that the rate constant is linearly proportional to temperature. The rate constant is increased 1.6 times by changing the temperature of the gas from 150 K to 295 K.

4. Conclusion

In this paper the temperature dependence of the rate constant for $I_2(B)$ deactivation by molecular nitrogen over the temperature range 150-295 K was obtained for the first time. It was found that the rate constant depends linearly on the temperature. The temperature dependence of the rate constant must be taken into account in order to convert LIF images into quantitative concentration maps in experiments with visualization of supersonic gas flows [2, 3], where high temperature gradients are realized.

At present the LIF method is used for diagnostics of gas flows in the combustion zones of different power systems [5-7]. As a fluorescent reporter, both stable molecules and radicals have been employed. To correctly interpret the images it is necessary to carry out additional processing that considers the lifetimes of the excited molecules in the combustion zone. The data reported here are of value for the analyses of flow field images taken within an oxygen-iodine laser that uses N_2 as the primary carrier gas.

Acknowledgements

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References

[1] N.H. Wrobel, N.H. Pratt, Laser Induced Sodium Fluorescence Measurements in a Turbulent Propane Diffusion Flame, 17 *International Symposium on Combustion, Leeds (1978).
[2] M.V. Zagidullin, V.D. Nikolaev, M.I. Svistun, N.A. Khvatov, G.D. Hager, Characteristics of the gain medium for an ejector COIL with supersonic nozzles for the driver buffer gas, Appl. Phys. A, 81 (2005) 311-315.
[3] V.D. Nikolaev, M.I. Svistun, M.V. Zagidullin, Ejector COIL, Proc. SPIE, 5479 (2003) 10-18.
[4] T. Van Marter, M.C. Heaven, D. Plummer, Measurement of the rate constant for the quenching of $I(^2P_{1/2})$ by $O_2(X)$ at 150 K, Chem. Phys. Lett. 260 (1996) 201-207.
[5] C.D. Carter, S. Hammack, T. Lee, High-speed planar laser-induced fluorescence of the CH radical using the $C^2\Sigma^+$ - $X^2\Pi(0,0)$ band, Appl. Phys. B, 116 (2014) 515–519.
[6] P. Nau, J. Krüger, A. Lackner, M. Letzgus, A. Brockhinke, On the quantification of OH*, CH*, and C_2* chemiluminescence in flames, Appl. Phys. B, 107 (2012) 551–559.
[7] R.P.C. Zegers, M.Yu.C. Bekdemir, N.J. Dam, C.C.M. Luijten, L.P.H. Goey, Temperature measurements of the gas-phase during surrogate diesel injection using two-color toluene LIF, Appl. Phys. B, 112 (2013) 7–23.